Analysis of the damping properties of high-transmission-ratio Cycloidal drives

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Abstract. Cycloidal drives are widely used in today's industries for drives where large reduction ratios are required. Drive-train dynamics plays an important role in their design. This paper presents a new methodology for assessing damping characteristics of Cycloidal drives and compares the natural frequencies obtained from experiments and theoretical/numerical calculations using Fast-Fourier-Transforms.

Introduction

Mechanical drives are mainly used for decreasing rotating shaft speeds, simultaneously increasing the output torque. Although many types of drives are in use where large reduction ratio is required, each has certain unique characteristics that cause comparably different responses to dynamic loads. Commonly used drives for these applications are Spur / Helical, Bevel and Worm gear drives arranged in multiple stages, Planetary (epicyclic) drives, Harmonic drives and Cycloidal drives. Of these, the Planetary, Harmonic and Cycloidal drives have become more popular over the last two decades. Harmonic and Cycloidal drives are more compact in comparison with planetary drives. Fig. 1 shows an exploded view of the components of a typical Cycloidal drive design. Cycloidal drives are used in a broad spectrum of applications in today's industries because of their compact size, high efficiency, minimal noise and high transmission ratio in a single stage [1, 2].

As features of their design, these drives have considerable torsional compliance, lost motion and specific damping behaviour. These characteristics play a vital role in the drive-train dynamics demanding proper understanding of the dynamic-force-responses (during operation under load) for their optimal design. To study the dynamic characteristics, a mathematical model is necessary. Torsional Stiffness [3] and Damping [4] values have to be assessed for mathematical modeling. The main types of damping found in literature are – Viscous damping, Coulomb (or Dry-friction) damping, Structural damping (in flanges and joints) and Material (or Hysteretic) damping [5].

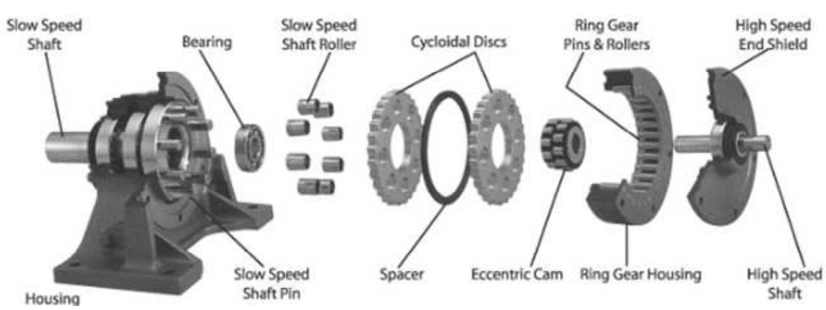


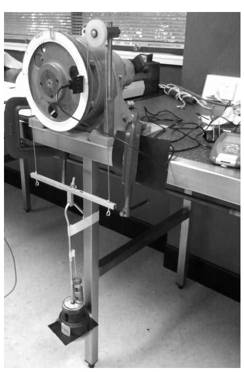
Fig. 1: Cycloidal drive components (Picture Source: http://www.gearmotor.com.my/cyclo-drive-spare-parts)

Previous author [4], Kosse, V., had presented a special experimental methodology for investigation of natural frequencies and damping properties of mechanical drives (epicyclic and

Cycloidal drives) with large reduction ratios. He had performed tests on a Cycloidal drive with output shaft locked, using an impact hammer, at various levels of static loading torques applied to the input end. This paper discusses a new experimental methodology for the investigation of damping and natural frequencies, using drop weights suspended by a weight hanger, at various input torques. The results were analysed and compared with those obtained by Fast Fourier Transform (FFT) analysis.

Experimental Setup and Procedures

A single stage Cycloidal drive of ratio 87:1 produced by Sumitomo Heavy Industries Ltd, Japan (Model CHH-4130-87) was used in this research. This is a compact unit which uses liquid lubricant, but for experimental purpose the lubricant was drained out [2]. This was done to exclude viscous damping caused by the lubricant. The output power of the drive is P = 1.14 kW at 1500 r.p.m, and the output torque is T_O = 585 Nm. The drive was secured on a workbench with two G-clamps. At the output end, the end-flange was removed and a special locking cap was added to hold the output shaft still. The input end has a pulley (as shown in Fig. 2), held by taper-lock and key joint. The pulley has a pitch radius of R_p = 0.118m. An accelerometer (Model: 3D-BTA, manufactured by "Vernier Software & Technology", USA), was attached to the front face of the pulley by means of two button magnets. One of the axes of the accelerometer orientated in the tangential direction was plugged into a data collection and analysis device – Labquest (Vernier Software & Technology, USA) to capture tangential acceleration of the pulley. Torsional impact loading was simulated using a small weight dropped by a certain height on a weight hanger hanging down a cable from the pulley. The falling weight would cause a shock in the drive-train and the response is recorded in the Labquest device. A trigger was set in the Labquest device to record any excitation that would cause an acceleration of greater than 0.05m/s^2. Thus, when the weight was dropped, the system response would trigger data collection automatically. A sample rate of 500 samples per second was set with total recording time duration of 0.25 seconds per impact (see Fig. 3). The weight suspension system was arranged to apply a couple of forces to the input pulley thus preventing any loads that cause bending of the input shaft (see Fig. 2).



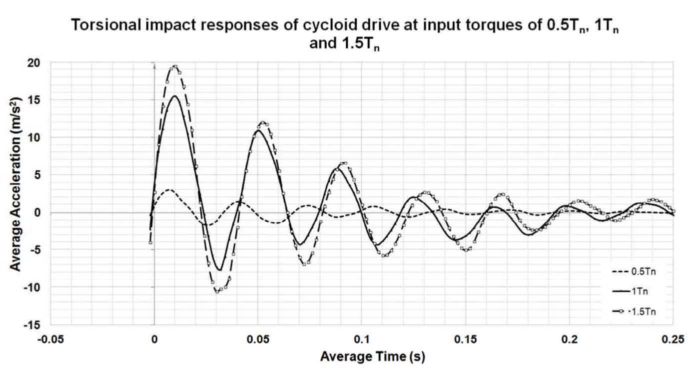


Fig. 2 (left): Cycloidal drive test set-up at Queensland University of Technology, Brisbane, Australia

Fig 3 (right): Response signals of Cycloidal drive subjected to input torques $0.5T_n$, $1T_n$ and $1.5T_n$ (T_n = nominal input torque = 7.257 Nm)

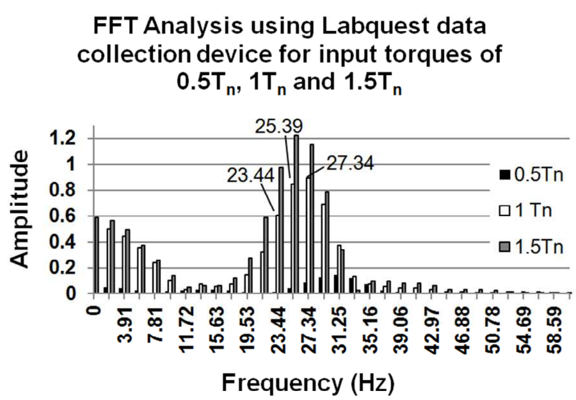
Using the manufacturer's recommended input speed, output torque and power rating, the input torque was calculated to be T_n =7.257 Nm [2].

The Cycloidal drive was loaded to the following torque levels for the tests: $0.5T_n$, $1T_n$, $1.5T_n$, $2T_n$, $2.5T_n$, $3T_n$, $3.5T_n$, $4T_n$ and $4.5T_n$ using appropriate weights in the weight hanger (inclusive of the drop-weight). Several trials were made with different drop-weights and drop-height to get a smooth undistorted response. Care was taken to avoid unwanted harmonics that disturbed the signal, as much as possible. The response was recorded in Labquest device. An average of 10 runs was taken for the purpose of analysis. Fig. 3 shows the impact response at 3 different input torques. "Logger Pro" (v3.8) software [6] shipped along with Labquest device (Vernier Software & Technology, USA), was used to transfer the results from the Labquest device to a computer and accurately measure the amplitudes and time periods of the first three decay curves of the response (as seen in Fig. 3) respectively. The same software was used to perform Fast-Fourier-Transform Analysis (FFT). The results were exported to "Microsoft Excel" (Microsoft Corporation, USA).

Using Excel software, the frequencies, logarithmic-decrements and damping ratios of the first three signals were calculated. Similar computation was performed for responses from other loading torques.

Analysis of Results

The results of FFT analysis calculated by Logger Pro 3.8 software and the variation of log-decrement across $0.5T_n$, $1T_n$ and $1.5T_n$ (plotted in Excel), are shown in Fig. 4 and Fig. 5 respectively. The calculated natural frequency (by measuring the period) of the responses at the above mentioned torques were: *28.8184Hz*, *24.3902Hz* and *20.4082Hz* respectively. Table 1 shows the comparison between the two sets.



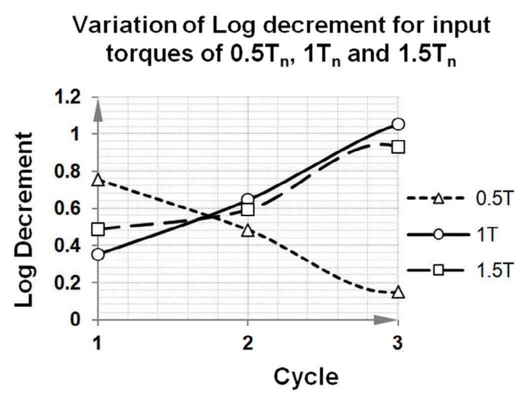


Fig. 4 (left): FFT analysis results; Fig. 5 (right) Log decrement variation across three different input torques.

Table 1: Comparison of calculated natural frequency from measured data with that of FFT

Input torque [Nm]	**Calculated Frequency [Hz]**	**FFT frequency [Hz]**
$0.5T_n$	28.82	27.34
$1T_n$	24.39	25.39
$1.5T_n$	20.41	25.39

Discussion and Conclusion

At high input torque loads, the components of the drive are subjected to high contact forces and hence the overall torsional stiffness increases. Higher excitation forces are necessary to produce good quality (high amplitude) responses for high input loads. As seen in Table 1, the observed natural frequency decreases for high impact forces which are in agreement with [4].

It is observed that the frequency of the signals increase as they die away into the electric-system noise. The log-decrement of $0.5T_n$ decreases progressively indicating the effects of viscous as well as structural damping at the joints of the links. The Cycloidal discs are mounted on an eccentric roller bearing as seen in Fig.1. Likewise, the pins in the ring-gear housing have clearances around them as well. Traces of lubricant left on contacting surfaces form minute wedges between mating parts which contribute to some level of viscous damping. At $0.5T_n$, the excitation force was not enough (evident from the small amplitude seen in Fig 3., because of the small drop weight used for impact) to overcome these damping factors resulting in the components vibrating within the lubricant wedge as shown in Fig. 6. With higher levels of loading, mating components exert contact pressure causing the lubricant traces to be expelled from the contact – resulting in Dry friction damping and hence the variation of responses is seen across increasing levels of input torques.

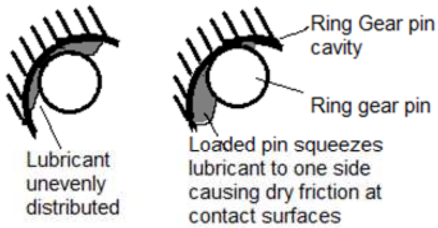


Fig. 6: Schematic showing the Ring gear and Pin interface

Cycloidal discs mesh with circular pins in the ring-gear housing. From the curvature point of view, the cycloid tooth-space is slightly wider than the pin for this design. As mentioned earlier, the pins have enough clearance in their ring-gear-housing as well. This provides ample room, for any alignment issues, as well as space for the pin to re-orient when loaded by the Cycloidal tooth-space contacting the pin at varying positions during its movement cycle. Lubricant traces can be present in spaces between contacting surfaces indicating that viscous damping is dominant.

As described, on the damping characteristics of high transmission ratio drives, experiments conducted on the output-shaft-locked Cycloidal drive, subjecting to various input loads, lead to the following conclusions:

- Natural frequencies at input torques less than the nominal are multiples of those for nominal.
- FFT analyses show that the values of natural frequencies are in good agreement with that obtained from decay curves.
- Log decrement value variations can be attributed to clearances between contacting surfaces and the presence of viscous damping.
- Using the damping ratios and log decrement values in mathematical modelling can provide a better understanding of the dynamic responses of the drive-train that can be used to optimise the drive's design.

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